METHOD AND APPARATUS FOR FORMING MILLIMETER WAVE PHASED ARRAY ANTENNA

FIELD OF THE INVENTION

[0001] The present invention relates to antennas, and more particularly to an electronically scanned, dual beam phased array antenna capable of operating at millimeter wavelengths and incorporating a corporate stripline waveguide structure.

BACKGROUND OF THE INVENTION

[0002] A phased array antenna is composed of multiple radiating antenna elements, individual element control circuits, a signal distribution network, signal control circuitry, a power supply, and a mechanical support structure. The total gain, effective isotropic radiated power and scanning and side lobe requirements of the antenna are directly related to the number of elements in the antenna aperture, the element spacing, and the performance of the elements and element electronics. In many applications, thousands of independent element/control circuits are required to achieve a desired antenna performance. A typical phased array antenna includes independent electronic packages for the radiating elements and control circuits that are interconnected through an external distribution network. Figure 1 shows a schematic of a typical transmit phased array antenna which includes an input, distribution network, element electronics and radiators.

[0003] As the antenna operating frequency increases, the required spacing between radiating elements decreases and it becomes difficult to physically configure the control electronics and interconnects within the increasingly tight element spacing. Relaxing the tight element spacing will degrade the beam scanning performance, but adequately providing multiple interconnects requires stringent manufacturing and assembly tolerances which increase system complexity and cost. Consequently, the performance and cost of the phased array antenna depends primarily on module packaging and distribution network interconnects. Multiple beam applications further complicate

this problem by requiring more electronic components and interconnects within the same antenna volume.

[0004] Phased array packaging architectures can be divided into tile (i.e., coplanar) and brick (i.e., in-line) styles. Figure 2 shows a typical tile-type architecture which exhibits components that are co-planar with the antenna aperture and which are assembled together as tiles. Figure 3 shows a typical brick-type architecture which uses in-line components that are perpendicular to the antenna aperture and are assembled together similar to bricks.

[0005] The assignee of the present application, The Boeing Company, has been a leading innovator in phased array module/element packaging technology. The Boeing Company has designed, developed and delivered many phased arrays which use tile, brick and hybrid techniques to fabricate radiator modules and/or distribution networks. The RF distribution network which provides electromagnetic wave EM energy to each of the phased array modules can be delivered in what is called "series" or "parallel". Series distribution networks are often limited in instantaneous bandwidth because of the various delays which the EM wave signal experiences during the distribution. Parallel networks, however, provide "equal delay" to each of the modules, which allows wide instantaneous bandwidth. However, parallel distribution increases in difficulty with a large number of radiator modules. The most common method to deliver equal delay to a group of phased array modules is a "corporate" distribution network. The corporate distribution network uses binary signal splitters to deliver equally delayed signals to 2^n modules. This type of distribution lends itself well to the tile array architecture that has been used extensively throughout industry.

[0006] The use of a corporate network in a tile architecture is limited by the module spacing. It becomes increasingly more difficult to distribute EM wave energy, DC power signals, and logic signals with tightly-packed modules of wide-angle beam scanning arrays at higher operating frequencies. Because the cost of RF power also increases with operating frequency, designers try to limit distribution losses by using low-loss transmission media. The lowest loss medium used is an air filled rectangular waveguide. However, such a waveguide requires a large volume and is not easily routed to individual sites (i.e., antenna

modules). Stripline conductors, depending on material parameters and dimensions, can exhibit as much as 5-10 times the amount of loss per unit length of waveguide as an air filled rectangular waveguide. However, a stripline waveguide is very compact and readily able to distribute RF energy to tightly-packed modules (i.e., radiating elements) that are separated by only a very small amount of spacing.

[0007] Air filled waveguides can be used exclusively in a series network to feed tightly packed antenna modules. Each air filled length of waveguide uses a series of slots in what is referred to as a "rail". The electrical length between the slots in a rail changes with the operating frequency. If the rail is used to form an antenna beam, the change in electrical length between slots causes the beam to shift or "squint" away from the intended angle as the operating frequency changes. As the number of slots in the rail is increased, the beam squint becomes more pronounced, thus reducing the instantaneous bandwidth even further. The slots in a rail also tend to interact with each other and make rail designs more difficult and complex. If the slots were isolated from each other, then the length of each slot needed for the desired coupling levels could be more easily determined. A rail also achieves its desired phase and amplitude distribution at a single center frequency and quickly degrades as the operating frequency deviates away from the center frequency.

[0008] For a phased array antenna, the phase errors introduced by series distribution networks can be adjusted for in the antenna module using phase shifters. To accomplish the adjustment or calibration, a priori knowledge of the instantaneous operating frequency is required. A look-up table is used to correct for the beam squint at various frequency points along the operating bandwidth of the array. The length of the rail determines the number of steps or increments required to adequately adjust the phase shifters. Longer rails cause more beam squint and narrower instantaneous bandwidth, which means that more frequency increments are required to calibrate the numerous antenna modules of the antenna.

[0009] A particularly challenging problem that The Boeing Company has been faced with, and which the antenna and method of the present invention overcomes, is developing a wide-beam scanning, Q-band phased array antenna

capable of operating at 44 GHz for MILSTAR communications. The MILSTAR communication protocol uses narrowband bursts of information frequency hopping over the 2 GHz bandwidth of operation. However, the use of a series fed waveguide and the differing beam squints requires knowledge of the next beam hopping frequency so that the appropriate delay can be obtained from the look-up table and applied to the phase shifters. Without such knowledge of the next beam hopping frequency, the series fed beam rail squints cannot be accurately determined. For security reasons, it is desirable for a phased array antenna system to not require specific frequency information for operation but instead to be able to operate over the entire bandwidth as a passive device. A new form of corporate feed waveguide network is therefore required which allows very tight module spacing, but which still does not require individual series fed rail beams squints to be calculated to maintain calibration of all of the individual module elements of the antenna.

SUMMARY OF THE INVENTION

[0010] The present invention is directed to a phased array antenna system and method which is capable of operating at 44 GHz and in accordance with the MILSTAR communication protocol without advance knowledge of the next beam hopping frequency. The system and method of the present invention accomplishes this by providing a phased array antenna incorporating the use of a new waveguide network. A first air filled waveguide structure feeds electromagnetic wave (EM) input energy into a second, dielectrically-filled waveguide structure. The second, dielectrically-filled waveguide structure feeds EM wave energy into a corporate stripline waveguide network. The corporate stripline waveguide network distributes the EM wave energy to a plurality of radiating elements of each of a corresponding plurality of independent antenna modules making up the phased array antenna of the present invention.

[0011] In one preferred form the first waveguide structure comprises a rectangular air waveguide structure. This structure feeds EM wave input energy from an input thereof into a plurality of outputs and divides the EM wave energy among the plurality of outputs. These outputs feed the second waveguide structure which, in one preferred form, includes a plurality of dielectrically-filled

circular waveguides. The second waveguide structure channels the EM wave energy to a corresponding plurality of inputs of the stripline waveguide structure where this EM wave energy is further successively divided before being applied to each of the radiating elements of the plurality of antenna modules of the antenna system. The use of the corporate stripline waveguide structure allows extremely tight element spacing to be achieved with only a very small reduction in efficiency of the system. The use of the corporate stripline waveguide structure further eliminates the need to apply independent beam squint corrections that would necessitate knowing the next beam hopping frequency in a MILSTAR application. The use of the corporate stripline waveguide network, in connection with the use of the first and second waveguide structures and suitable phase shifters, effectively provides the same delay to each radiating element of the antenna system, which also significantly simplifies the complexity of the electronics needed for the antenna system.

[0012] Advantageously, the antenna system of the present invention is calibrated using a single look-up table; therefore, a priori knowledge of the next beam hopping frequency is not needed. The antenna system of the present invention provides excellent beam side lobe levels at both boresight and at a 60 degree scan angle. The beam patterns produced by the antenna system of the present invention also exhibit excellent cross-polarization levels.

[0013] Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0015] Figure 1 is a simplified block diagram of a typical transmit phased array antenna system;

[0016] Figure 2 is a simplified perspective view of certain of the components of a tile-type phased array antenna system;

[0017] Figure 3 is a simplified perspective view of certain components of a brick-type phased array antenna system;

[0018] Figure 4 is a simplified perspective view of a phased array antenna in accordance with a preferred embodiment of the present invention;

[0019] Figure 5 is an exploded perspective view of the antenna system feed network of Figure 4;

[0020] Figure 5A is a partial cross-sectional view of a tapered transition dielectric plug inserted within the tapered transmission plate and the WDN feed plate;

[0021] Figure 6 is a plan view of the waveguide distribution network input plate which forms a 1X4 air filled rectangular waveguide feed structure;

[0022] Figure 7 is an enlarged plan view of the stripline waveguide printed circuit board;

[0023] Figure 8 is a highly enlarged portion of the circuit board of Figure 7;

[0024] Figure 9 is a graph of the far-field amplitude of the antenna of the present invention at a zero degree scan angle (i.e., along the boresight); and

[0025] Figure 10 is a graph of the far-field amplitude of the antenna system of the present invention at a 60 degree scan angle.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0026] The following description of the preferred embodiment(s) is merely exemplary in nature and is in no way intended to limit the invention, its application, or uses.

[0027] Referring to Figure 4, an antenna system 10 in accordance with a preferred embodiment and method of the present invention is shown. The antenna system 10 forms an antenna able to operate at millimeter wavelengths, and more particularly at 44 GHz (Q-band) and in accordance with the MILSTAR protocol without requiring advance knowledge of the next beam hopping frequency being employed in a MILSTAR application. The antenna system 10 forms a dual beam system having a plurality of 524 independent antenna

modules very closely spaced relative to one another to enable operation at millimeter wave frequencies, and more preferably at about 44 GHz, without suffering significant beam degradation and performance at scan angles up to (or exceeding) 60 degrees. The antenna system generally includes a chassis 11 within which is supported a feed network 12 and associated electronics (not shown).

[0028] Referring to Figure 5, an exploded perspective view of the major components of the feed network 12 of the antenna system 10 is illustrated. The EM wave input signal is generated by a microwave generator (not shown) to an input end 14a of a waveguide input transition member 14. The EM wave signal travels through a rectangular bore to a rectangular output 14b. The waveguide input transition member 14 is inserted through an aperture 16a in a rear, mechanical, co-thermal spacer plate 16 and the output 14b is connected to a waveguide distribution network (WDN) input plate 18. The WDN input plate 18 has a waveguide 19 having an input 19' and outputs 19a-19d. The WDN input plate 18 is coupled to a bottom rectangular feed plate 20 having a plurality of four rectangular waveguide slots 20a-20d that align with outputs 19a-19d. The EM wave input signals are channeled from the WDN input plate 18 through waveguide 19, through slots 20a-20d and into a WDN tapered transmission plate 22. Transmission plate 22 has a plurality of 524 generally circular recesses 24 that do not extend completely through the thickness of plate 22. Plate 22 also includes four apertures $24a_1 - 24a_4$ that extend completely through the plate 22. The four apertures $24a_1 - 24a_4$ are aligned with the four waveguide slots 20a-20d. Each one of the 524 recesses 24 and four apertures $24a_1 - 24a_4$ are longitudinally aligned with a corresponding plurality of apertures 26 in a WDN feedplate 28. A plurality of 524 ¼ wave, circular backshort dielectric plugs 30 (shown merely as a representative plurality in Figure 5) fill 524 of the apertures 26 and also fill 524 of the apertures 24 of transmission plate 22. A plurality of four tapered transition dielectric plugs 32 extend through four of the apertures 26a-26d. The apertures 26 filled by tapered transition dielectric plugs 32 are those apertures that are longitudinally aligned with apertures $24a_1 - 24a_4$ of tapered transmission plate 22 and rectangular slots 20a-20d of rectangular feed plate 20. Dielectric plugs 32 also extend partially into apertures $24a_1$-$24a_4$ when

the feed network 12 is fully assembled. This is illustrated in Figure 5a where plug 32 can be seen to have a circular head portion 32a and a conical body portion 32b. The circular head portion 32a fills an associated aperture (i.e., one of apertures 26a-26d) in the WDN feedplate 28 and the conical body portion 32b rests within an associated one of the apertures $24a_1$-$24a_4$ in the WDN tapered transmission plate 22.

[0029] The apertures $24a_1$-$24a_4$ in the WDN tapered transmission plate 22 begin as rectangular in cross section on the back side of transmission plate 22 (i.e., the side not visible in Figure 5), and transition into a circular cross sectional shape on the side visible in Figure 5. This, together with the conical portions of plugs 32, serves to provide a rectangular-to-circular waveguide transition area for the EM wave energy traveling through the plate 22. In one preferred form plugs 32 have a dielectric constant of preferably about 2.5. Accordingly, WDN transmission plate 22 functions as a rectangular-to-circular waveguide transitioning component.

[0030] With further reference to Figure 5, a WDN stripline printed circuit board (PCB) 34 is secured over an output side of WDN feedplate 28 and forms a means for dividing the EM wave energy channeled through each of the four apertures 24a to a corresponding input trace of a corporate stripline distribution network 34a formed on the WDN stripline PCB 34. A WDN circular waveguide plate 36 is secured over the WDN stripline PCB 34. WDN circular waveguide plate 36 includes 528 circular apertures, designated generally by reference numeral 38, with four apertures 39 each filled with one circular backshort dielectric plug 40 and one circular backshort aluminum (conductive) plug 42. The filled apertures 39 are those that are longitudinally aligned with slots 20a-20d of rectangular feed plate 20 and apertures $24a_1$-$24a_4$ of tapered transmission plate 22. The remaining 524 apertures denoted by reference numeral 38 are filled with circular waveguide dielectric plugs 44 (shown merely as a representative plurality in Figure 5). Plugs 44 preferably are comprised of Rexolite® plastic. A pair of module alignment pins 46 extend through apertures 36a in waveguide plate 36, apertures 34b in WDN stripline circuit board 34, apertures 28a in feed plate 28, apertures 22a in tapered transition plate 22, apertures 21 in rectangular feed plate 20, apertures 18a in WDN input plate 18 and apertures 16b in spacer plate

16 to maintain alignment of the large plurality of apertures of the components 22, 28, 34 and 36 illustrated in Figure 5.

[0031] With brief reference to Figure 6, the WDN input plate 18 can be seen in greater detail. WDN input plate 18 includes the rectangular, air-filled waveguide 19 having input 19' that receives EM wave energy from the output end 14b of waveguide input transition 14 of Figure 5. The rectangular, air-filled waveguide 19 takes this EM wave input energy and divides it between the four rectangular output slots 19a, 19b, 19c, and 19d. The EM wave energy exiting through rectangular slots 19a-19d is channeled through rectangular slots 20a-20d of WDN bottom rectangular feed plate 20 shown in Figure 5. WDN input plate 18 is preferably formed from a single sheet of metal, and more preferably from aluminum, although it will be appreciated that other suitable metallic materials such as gold could be employed. Spacer plate 16 is also preferably formed from metal, and more preferably aluminum, as are plates 22, 28 and 38.

[0032] Figure 7 is a plan view of the stripline printed circuit board 34. Input traces $34a_1$, $34a_2$, $34a_3$ and $34a_4$ are aligned with apertures $24a_1$-$24a_4$ of the waveguide tapered transition plate 22, respectively. More specifically, the input traces $34a_1$-$34a_4$ are each disposed to line up parallel with the electromagnetic field in each of apertures 26a-26d. Inputs $34a_1$-$34a_4$ each feed a plurality of EM wave radiating elements 56 (i.e., independent antenna modules) through a plurality of "T-junctions" 35 (denoted in Figure 8) formed by the conductive portions (i.e., stripline traces) of the circuit board 34. More specifically, each of the "T-junctions" 35 of the WDN stripline PCB 34 operate as binary signal splitters to successively (and evenly) divide the EM wave input energy received at each of inputs $34a_1$-$34a_4$ into smaller and smaller subpluralities that are eventually applied to each radiating element 56. Figure 8 illustrates a representative portion of the corporate EM wave distribution network formed by the stripline PCB 34. Input $34a_2$ can be seen to feed radiating elements 56a-56p. Two representative T-junctions 35 are shown in Figure 8.

[0033] Input $34a_1$ feeds 254 of the radiating elements 56, input $34a_2$ feeds 126 of the radiating elements 56, input $34a_3$ feeds 96 of the radiating elements 56 and input $34a_4$ feeds 48 of the radiating elements 56.

[0034] In operation, EM wave energy is radiated by each of the radiating elements 56 through the apertures 38 in the WDN circular waveguide plate 36, and also back towards the WDN feed plate 28. The plugs 30 have a preferred dielectric constant of about 2.5. Electromagnetic energy travels through plugs 30 and is reflected at the very bottom wall of each of the 524 recesses in transmission plate 22 back toward circuit board 34 and continuing on through apertures 38 in WDN circular waveguide plate 36. In one preferred form plugs 30 are made from Rexolite® plastic material. Plugs 40, which are preferably comprised of Rexolite® plastic, as well as plugs 42, which are preferably metal, and more preferably aluminum, fill apertures 39. The EM wave energy from apertures 26a-26d travels through plugs 40 and is reflected by plugs 42 back towards input traces $34a_1 - 34a_4$ of the circuit board 34. Plugs 30, 32, 40 and 44 each have a dielectric constant of preferably about 2.5 and enable operation of the antenna system 10 at millimeter wave frequencies with the very tight element spacing used in the antenna system.

[0035] With brief reference to Figures 9 and 10, the performance of the antenna system of the present invention can be seen. Referring specifically to Figure 9, the far-field performance of the antenna system 10 can be seen with the antenna system operating at 44.5 GHz and at a zero degree scan angle. Referring to Figure 10, the antenna system 10 is shown operating at 44.5 GHz but with a 60 degree scan angle. The resulting sidelobe levels, represented by reference numerals 58, are well within acceptable limits and the beams shown in Figures 9 and 10 exhibit good cross-polarization levels. Performance is similar across a design bandwidth of 43.5 – 45.5 GHz.

[0036] The antenna system 10 of the present invention thus enables a phased array antenna to be formed with the radiating elements 56 being very closely spaced to one another to be able to perform at millimeter wave frequencies, and more particularly at 44 GHz. Importantly, the antenna system 10 does not require knowledge of the next beam hopping frequency when used in a MILSTAR communications protocol. The corporate WDN stripline printed circuit board 34 of the antenna system 10 enables the extremely close radiating element 56 spacing needed for excellent antenna performance at millimeter wave

frequencies while allowing the amplitude and phased delays applied to each radiating element 56 to be determined from a single look-up table.

[0037] It will also be appreciated that while the terms “input” and “output” have been used to describe portions of the components of the antenna system 10, that this has been done with the understanding that the antenna has been described in a transmit mode of operation. As one skilled in the art will readily understand, these terms would be reversed when the antenna system 10 is operating in a receive mode.

[0038] While various preferred embodiments have been described, those skilled in the art will recognize modifications or variations which might be made without departing from the inventive concept. The examples illustrate the invention and are not intended to limit it. Therefore, the description and claims should be interpreted liberally with only such limitation as is necessary in view of the pertinent prior art.